Theory of radiation-induced attenuation in optical fibers

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Abstract

A new mathematical model for describing radiation-induced attenuation in optical fibers is presented. Unlike the existing empirical power law, the new expression is dose-rate dependent and can be used to predict low-dose-rate induced fiber loss occurring in space from the normally high-dose-rate results obtained in a ground-based laboratory. The new theory is in good agreement with the experiment.

1. Introduction

It is well-known that optical fibers have several advantages over coaxial cables, including high bandwidth, light weight, being immune to electromagnetic interference (EMI), and being resistant to corrosive chemicals. Deployment of optical fiber cables in future space missions and nuclear plants will soon become a reality as a result of many research works.’- [11] These works have shown that radiation may induce both recoverable attenuation and non-recoverable residual attenuation in fibers. But, in general, optical fibers arc suitable for space applications. Recently, the advent of several ncw radiation-hardened fibers further makes the usc of optical fibers in space practical,

An empirical expression[1,10] for describing radiation-induced attenuation has been widely used in the past. However, this expression is not explicitly dose-rate dcpcndcnt, while, in general, the radiation-induced fiber loss is. The radiation dose rate encountered in space orbits is, in general, relativel y lower than the dose rate generated in a ground-based laboratory. As a result, it is desired to have a theory which can predict the radiation-induced attenuation in fibers deployed in space from the results obtained in a ground-based laboratory. An extrapolation method for obtaining low-dose rate results from high-dose rate data has been reported previous] y. [11]

In this paper, wc present a ncw theoretical model for predicting radiation-induced fiber loss, based on the linear superposition principle. This ncw theoretical model yields a dose-rate dependent expression for radiation-induced fiber loss. The special case of constant dose rate is considered specifically and compared with experimental results. The part of data taken during radiation on is fitted with the ncw expression to determine the parameter values of the expression. Then the recovery part of the data is compared with the theoretical curve plotted using the parameter values obtained from curve fit. This ncw theory can be used to estimate the radiation-induced fiber loss for any dose-rate pattern. In particular, it is useful for computing the fiber loss to be expected in the low-dose rate space environment, using data generated in a high dose-rate, ground-based laboratory.

2 Existing Theory

The radiation-induced attenuation in optical fiber has been empirically found to obey the power law,[1,10]

$$A = aD^b \qquad (1)$$

where A is the induced loss, D is the total dose of radiation, and a and b are constants. Eq. (1), which has been widely used to describe experimental results, states that the radiation-induced loss in fibers is a power function of the total dose. All other dependent variables such as dose rate are embedded in parameters a and b which are to be estimated by fitting Eq. (1) to experimental data.

When radiation ceases, the total induced loss will recover partially due to thermal annealing. The recovery of the induced loss can be described by the following equation,[1,10]

$$A = (A_o - A_f)[1 + ct]^{-1/(n-1)} + A_f \qquad (2)$$

where A_o and A_f are the initial and final values of the induced loss, n is the material-dependent kinetics order, and

$$c = (1/\tau)(2^{n-1} - 1), \qquad (3)$$

where τ is the half-height lifetime of the recovery process, i.e. the time it takes for $A-A_f$ to reduce to $\frac{1}{2}(A_o-A_f)$ from A_o-A_f.

Since the recovery will begin as soon as the radiation-induced loss occurs, the total radiation induced loss should also depend on the dose rate. For the sake of argument, consider two extreme cases in which the dose rates are approaching infinity and zero, rcspcctivcly, given a fixed total dose. Then in the former, the radiation-induced color centcrs have little time to decay over the whole event, Thus, the total induced loss is essentially equal to that caused by the total induced color centers. In the latter, the induced color centcrs have much time to decay over the whole event. ‘1’bus, the total induced loss is cssentiall y given by the residual val uc. These two cases show that the induced attenuation is dose-rate dcpcndcnt indeed. In order to predict the induced loss for any dose rate pattern, the expression used must bc explicitly dose-rate dcpcndcnt. In the following, such a ncw expression is derived theoretically.

3. New Theory

Our theoretical model is based on the assumption that the radiation-induced color-center generation (or loss phenomenon) is a linear effect. l’bus, the overall effect can bc treated as the superposition of many independent events occurring sequentially in infinitesimal time intervals. If these events occur between time equal to 0 and t, the standard mathematical expression for such a statement is

$$R(t) = \int_0^t f(t')h(t-t')dt' \qquad (4)$$

where $h(t-t')$ is tbc impulse function representing the response of the system to *a unit* of excitation over the interval $t-t'$, $f(t')$ is the excitation function representing the number of units of excitation rate at t', and R(z) is the total response function describing the total response from O to t.

Let us assume that the impulse function, $h(t-t')$, is proportional to the right side of Eq. (2) and the excitation function, $f(t')$, is given by the time-dcpcndcnt dose rate function, D‘(t’). Then substituting these functions into Eq. (4) yields the total radiation-induced attenuation in a fiber,

$$A(t) = \int_0^t \left\{ D'(t')(a_o - a_f)[1 + c_i(t - t')]^{\frac{-1}{n-1}} + a_f \right\} dt \qquad (5)$$

where a_o and a_f arc the microscopic versions of A_o and A_f in Eq. (2), respectively. c_i has the same definition as c in Eq. (3), except the parameter τ (or τ_i in Fig. 1) now represents the half-height lifetime of an infinitesimal excitation event.

in general, using numerical method, Eq. (5) can be used to predict the radiation-induced loss for any dose-rate function $D'(t')$. This includes the special case of the recovery process in which $D'(t')=0$ for t' greater than the time at which the radiation ceases. In the special case of constant dose rate, the right side of Eq. (5) can be readily integrated and becomes

$$A(t) = D'\left\{ \frac{a_o - a_f}{c} \frac{n-1}{n-2} [(1+ct)^{\frac{n-2}{n-1}} - 1] + a_f t \right\} \qquad (6)$$

The main difference between the new formula, Eq. (6), and the existing power law, Eq. (1), is that Eq. (6) is explicitly dose-rate- and kinetics-order-dependent.

To further compare Eq. (6) with Eq. (1), two special cases, t approaches zero and infinity, arc considered below. As t approaches zero, Eq. (6) reduces to a linear equation,

$$A = a_o D \qquad (7)$$

Thus, Eq. (6) dots not converge to the exact form of Eq. (1) in this regime. However, as t approaches infinity, Eq. (6) becomes

$$A = a' D^{b'} + a_f D \qquad (8)$$

where a' and b' arc given by

$$a' = (a_o - a_f)\frac{n-1}{n-2}c^{\frac{-1}{n-1}}D'^{\frac{1}{n-1}} \quad (9)$$

$$b' = \frac{n-2}{n-1}, \quad (10)$$

respectively. In the case of $a_o >> a_f$, Eq. (8) dots converge to power law, Eq. (1).

After the radiation is turned off, the color centers will decay via recombination and the fiber will recover from the induced loss with a permanent induced residual loss as in Eq. (2). For the special case of constant dose rate, the recovery of the induced loss as a function of time can be explicitl y derived from Eq. (S) as well.

Let us assume the radiation is ceased at time t_o and wc arc interested in finding out the induced fiber loss after this point at time t. Then Eq. (4) can be rewritten as

$$R(t) = \int_0^{t_o} f(t')h(t-t')dt' \quad (11)$$

Note that the upper limit of the integral in Eqs (4) and (11) arc different. '1'bus, the recovery equation can be readily derived from Eq. (5) as given by

$$A(t) = D'\frac{a_o - a_f}{c}\frac{n-1}{n-2}\left[(1+ct)^{\frac{n-2}{n-1}} - \left(1+c(t-t_o)\right)^{\frac{n-2}{n-1}}\right] + a_f D \quad (12)$$

The half-height lifetime of recovery is not explicitly indicated in Eq. (12). However, it can be evaluated from the plot of this equation. As expected, when the total elapsed time is much larger than the radiation time, i.e. $t >> t_o$, Eq. (12) approaches the residual value, $a_f D$.

4. Experimental Testing of the New Theory

To test the ncw theory, the cxpcrimcntal data from a previous work[6] arc fitted by Eq. (6) as shown in Fig. 1. Then the parameter values obtained by curve fit arc used in Eq. (12) to plot the rccovcry curve and compared with the cxpcrimcntal result. The data was obtained using Co^{60} to bombard a multimode optical fiber cable at room tcmpcraturc with a constant dose rate, 15.5 rad/sec.

Reasonably good fit is observed in Fig. (1). The infinitesimal rccovcry time τ_t (0.7 1 milli-seconds) obtained from curve-fit is much shorter than the macroscopic rccovcry time (670 seconds). The theoretically predictcd rccovcry curve as shown in Fig 2 is also reasonably consistent with the cxpcrimcntal data. These results strongly indicate that the linear superposition principle based theory described above is adequate for describing the radiation-induced fiber loss effect.

To compare the ncw theory, Eq. (8), with the existing theory, Eq. (1), the data in Fig. (1) were also fitted with Eq. (1) and yield a=O.019 and .! =0 .68. On the other hand, from Eqs (9) and (1 O), wc obtain the equivalent parameter values a'=0.014 and b'=0.66 which arc close to the values of a and b. This comparison is not expected to yield the same parameter values, because Eq. (8) is a reduced form of Eq. (6) for t approaches infinity.

5. Summary and Conclusions

Wc have presented a ncw theoretical model for predicting radiation-induced fiber loss, based on the linear superposition principle. This ncw theoretical mode] yields a dose-rate dcpcndcnt expression for radiation-induced fiber loss. The special case of constant dose rate was considered specifically and compared with cxpcrimcntal results. A good agreement was observed between the theory and the experiment. This ncw theory can bc used to estimate the radiation-induced fiber loss for any dose-rate pattern. In particular, it is useful for computing the fiber loss to be expected in the low-dose rate space environment, using data generated in a high dose-rate, ground-based laboratory.

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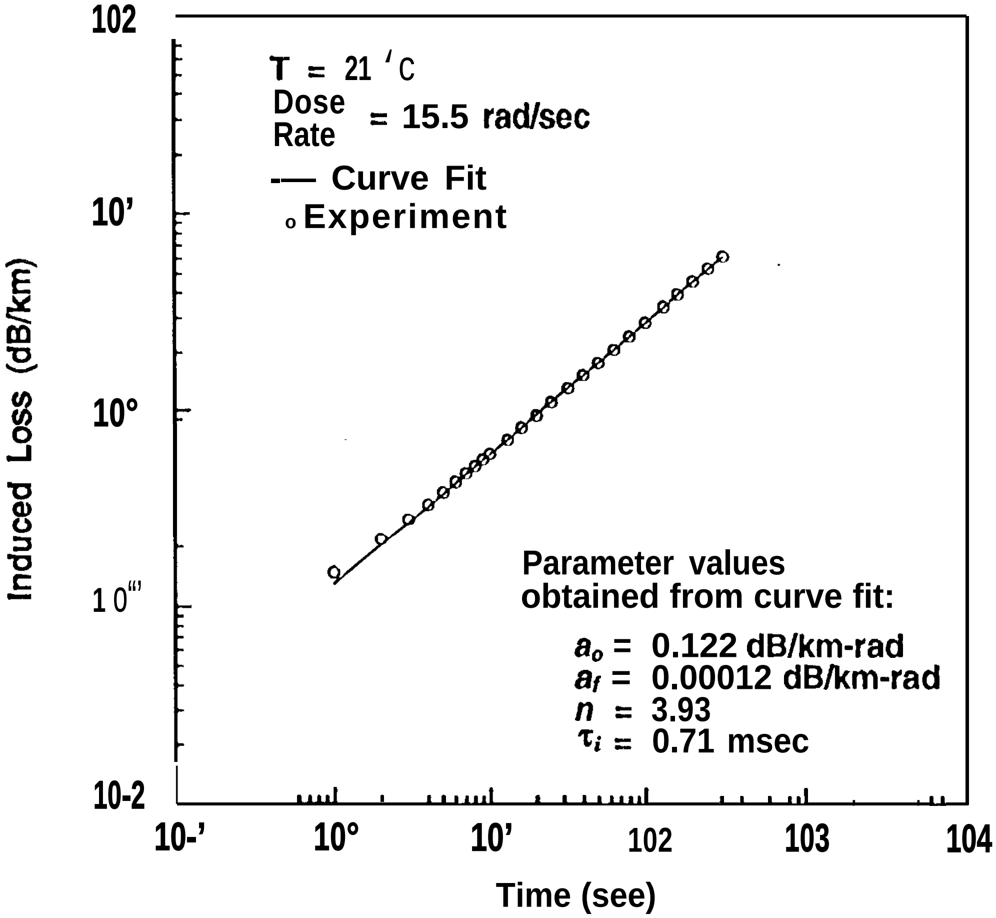
Figure captions:

Figure 1. Curve fit of the experimental data using the new theory.

Figure 2. Theoretical and experimental plot of the recovery curve.



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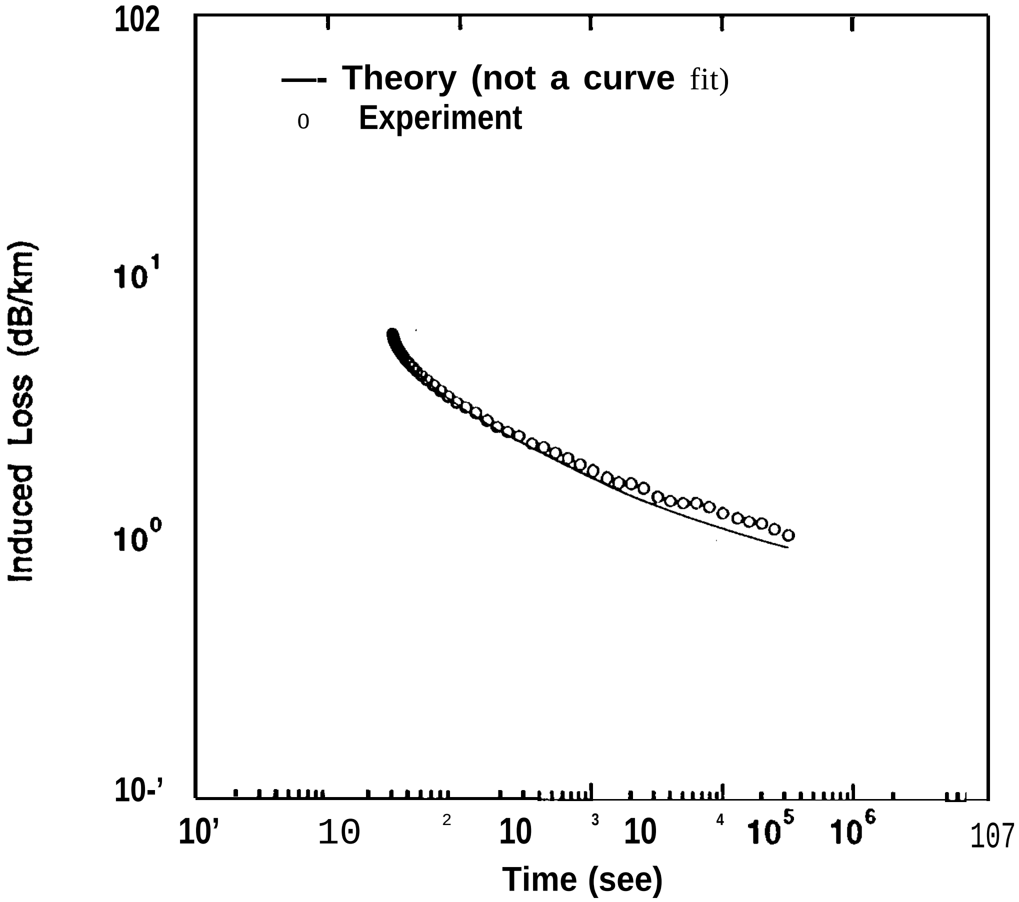

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